
**L→H Transition Criterion:**
A 3D Nonlinear Simulation Study

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Introduction

- L-H transition phenomenology
  - Sudden bifurcation to high confinement (H-mode)
  - Studied for ~32 years
  - Theory perspective-based on transport bifurcation and profile self-organization via predator-prey dynamics
  - Main paradigm: ExB flow shear ($\omega_{\text{ExB}}$) suppression of the turbulence
    - $\omega_{\text{ExB}} > \gamma_{\text{lin}} \rightarrow$ turbulence suppressed and H-mode sustained
  - Unknown
    - Trigger mechanism
    - Transition criterion based on microphysics (need predictive capability)

- Main questions
  - What triggers the transition?
  - How the transition evolves?
  - How predict transition, and power threshold?

To be explained in the present talk
H-mode and L-H transition

- H-mode: enhanced plasma confinement with edge transport barrier (ETB)

- H-mode history/phenomenology (1982-2014)
  - Wagner (1982): first discovered at ASDEX-U
  - Er shear layer at edge, fluctuation decrease, existence of power threshold ($P_{th}$)
  - Predator-Prey paradigm [Diamond, PRL, 1994; Kim & Diamond, PRL 2003]
    - Zonal flow (ZF): predator, turbulence: prey, mean flow: another predator
    - ZF triggers the transition, while mean flow sustains the barrier

- Why H-mode is important for fusion?
  - Practical reason: can reduce reactor size
  - H-mode driven high pedestal height
    → high fusion performance
Experimental evidence of a role of turbulence-driven (ZF) flow in triggering L-H transition

- Tynan (2013) and Manz (2012)
  - Normalized Reynolds power
    \[ R_T = \frac{\langle \tilde{v}_r \tilde{v}_\theta \rangle \langle V_{ZF}^{LE} \rangle}{\gamma_{eff} \langle \tilde{v}_1^2 \rangle} \]
    meaning a ratio of kinetic energy transfer from turbulence into ZF to the turbulence input power
  - Turbulence collapse condition
    \[ R_T > 1 \]
  - Experimental results show that L-H transition occurs when \( R_T > 1 \)
- Yan (2014) reported a similar finding at DIII-D
Main results

- 3D flux-driven simulation of edge transport barrier (ETB) formation shows that

1. ETB forms once input power exceeds a threshold value
   - Steep pressure pedestal, deep Er well appear when $P_{in} > P_{th}$
   - $Q$ versus $-\nabla P$ curve shows a feature of first-order phase transition

2. ETB transition is triggered by turbulence-driven flow shear
   - $R_T > 1$: criterion for the trigger of the transition
   - Burst of the turbulence-driven flow shear appears just prior to the transition point

3. Time sequence of the transition is clear
   1) Peaking of the normalized Reynolds power ($R_T > 1$):
   2) Turbulence suppressed and pressure gradients increased
   3) Mean flow shear ($\langle V_E \rangle \text{ from } \nabla P$) rises: **sustain H-mode**

→ Microphysics ($R_T$) may govern L→H transition!
3D model using BOUT++

- Electrostatic model with resistive ballooning (RBM) turbulence
  - Two field (vorticity, pressure) reduced MHD equations (constant density)
  - Flux driven, self-consistently evolving pressure profile

- Vorticity (U)
  \[ \frac{\partial U}{\partial t} = -\vec{V}_E \cdot \nabla U - B^2 \nabla \parallel J \parallel B + \vec{b} \times \vec{k} \cdot \nabla P + \mu \nabla^2 U - \mu_{\text{neo}} (U_{0,0} - U_P), \]

- Pressure (P)
  \[ \frac{\partial P}{\partial t} = -\vec{V}_E \cdot \nabla P + \chi \nabla^2 P + \chi_{\text{neo}} \nabla^2 P + S_0(r) - S_1 P_{0,0} \]

  - Overall results are independent of the particular source and sink profiles
  - For transport coefficients, we use \( \chi_\parallel = 0.1, \chi_{\text{neo}} = \mu_\perp = 3.0 \times 10^{-6} \)

Neoclassical poloidal flow damping accounting for self-consistent flow

Since \( v_{i,*} \sim n T_i^{-2} \sim P^{-2} \), \( k_{\text{neo}} (v_{i,*}) \rightarrow k_{\text{neo}} (P) \), \( \mu_{\text{neo}} (v_{i,*}) \rightarrow \mu_{\text{neo}} (P) \)

Heat source \( \rightarrow \) models SOL loss
Edge transport barrier (ETB) forms when $P_{\text{in}} > P_{\text{th}}$

- ETB forms at $x \sim 0.95$ for $P_{\text{in}} > P_{\text{th}}$ [Park, H-mode Workshop, 2013]
- Steep pressure pedestal
- Deep $E_r$ well
- Discontinuity in slope of $Q$ versus $-\nabla P$ graph
  - A feature of first-order phase transition
- Similar simulation result of ETB formation has been reported [Chone, PoP, 2014]
Power ramp up simulation shows the turbulence collapse at $t=t_R$ via an intermediate phase

- Limit-cycle oscillation (LCO) appears prior to the transition
- Turbulence is continuously growing and peaks just before the transition
- ExB flow shear changes abruptly near the transition (yellow shaded area)
$R_T > 1$ for the trigger of the transition at $t=t_R$: fluctuation energy $\rightarrow$ flow $(m=n=0)$ energy

- Turbulence collapse condition ($\frac{\partial \tilde{V}^2}{\partial t} < 0$) $\Rightarrow R_T \geq 1$
- $R_T > 1$ means the conversion of fluctuation energy into flow energy faster than turbulence energy increase

Reynolds work (simulation)

- Tynan (2013)

$D_\alpha$ drop

$R_T$ at edge
Simulation shows a similar sequence of the transition to that observed on C-Mod (Cziegler, 2014)

- $R_T > 1$ at $t = t_R$ → an increase of pressure gradient.
  - $R_T > 1$ at $t = t_R$ triggers the transition
  - Turbulence collapse → an increase of $\nabla P$
Microscopic time sequence of the transition: $\nabla P$, $\text{ExB}$ flow shear ($\omega_{\text{ExB}}$), and linear growth rate ($\gamma_{\text{lin}}$)

- $R_T > 1$ causes the surge of the turbulence-driven flow shear at $t=t_R$
- Increase of pressure gradient precedes mean flow shear development
- Positive feedback between $\nabla P$ and $\omega_{\text{ExB}}$ begins at $t=t_P$
- Mean shear criterion ($\omega_{\text{ExB}} > \gamma_{\text{lin}}$) is satisfied later, at $t=t_C \rightarrow$ H-mode sustained afterward

\[ \tau_A \]
Preliminary electromagnetic three-field results

- Simulation of ETB formation using three-field model
  - Two-field model + Ohm’s law for perturbed vector potential ($\psi$)
    \[ \frac{\partial \psi}{\partial t} = -\nabla_{\parallel} \Phi + \frac{1}{S} \nabla_{\perp}^2 \psi, \]
  - Profiles of $\mu_{\text{neo}}$ and $k_{\text{neo}}$ are fixed in time in this simulation
  - ETB occurs for $P_{\text{in}} = 2.0$ as seen in right figures
  - Suggests that the transition physics as found in electrostatic case may also apply for the electromagnetic case (Work is in progress)
Conclusions and discussions

- First 3D turbulence simulation to explicitly show
  - ETB formation for $P_{in} > P_{th}$
  - The criteria $R_T > 1$ is the trigger of the $L \rightarrow H$ transition
    - $\text{Microphysics (} R_T \text{) may govern } L \rightarrow H \text{ transition process}$
  - Detailed time sequence of the $L-H$ transition
    - $R_T > 1 \rightarrow$ the surge of the turbulence-driven flow shear
    - An increase of pressure gradient $\rightarrow$ mean flow shear development via positive feedback
    - $\omega_{\text{ExB}} > \gamma_{\text{lin}} \rightarrow$ steady $H$-mode sustained

- Future works
  - Microscopic parameter trends in $R_T$ and their relation to $L \rightarrow H$ transition power threshold scaling
  - Formation of sudden deep (in time) $R_T$ just prior to the transition
  - $H \rightarrow L$ back transition and hysteresis
  - Electromagnetic case

Microphysics ($R_T$) may govern $L \rightarrow H$ transition process